

# A New Radio Detection of the Bursting Source GCRT J1745–3009

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## ABSTRACT

GCRT J1745–3009 is a transient bursting radio source located in the direction of the Galactic center, discovered in 330 MHz VLA observations from 2002 September 30–October 1 by Hyman et al.. We have searched for bursting activity from GCRT J1745–3009 in nearly all of the available 330 MHz VLA observations

of the Galactic center since 1989 as well as in 2003 GMRT observations. We report a new radio detection of the source in 330 MHz GMRT data taken on 2003 September 28. A single  $\sim 0.5$  Jy burst was detected, approximately  $3\times$  weaker than the five bursts detected in 2002. Due to the sparse sampling of the 2003 observation, only the decay portion of a single burst was detected. We present additional evidence indicating that this burst is an isolated one, but we cannot completely rule out additional undetected bursts that may have occurred with the same  $\sim 77$  min. periodicity observed in 2002 or with a different periodicity. Assuming the peak emission was detected, the decay time of the burst,  $\sim 2$  min, is consistent with that determined for the 2002 bursts. Based on the total time for which we have observations, we estimate that the source has a duty cycle of roughly 10%.

*Subject headings:* Galaxy: center — radio continuum — stars: variable: other

## 1. Introduction

Transient radio emission has been detected from many astronomical sources including flare stars, brown dwarfs, masers, gamma ray bursts, pulsars, supernovae, neutron star and black-hole X-ray binaries, and active galactic nuclei. Efficient *blind* searching for radio transients requires a telescope for which the product of the field of view  $\Omega$ , the sensitivity or collecting area  $A$ , and the ratio of the total observing time to the time resolution  $T/\delta t$  is “large.” Generally, radio telescopes have been able to maximize only two of these three quantities. Thus, the majority of radio transients have been found by either monitoring objects thought to be potential radio emitters (e.g., flare stars and brown dwarfs) or by followup observations of objects detected at higher energies (e.g., X-ray binaries and gamma-ray bursts). Recent developments in low frequency imaging techniques have produced wide-field images ( $\approx 3^\circ$  FWHM) with uniform and high resolution across the field (LaRosa et al. 2000; Nord et al. 2004) thereby enabling efficient searches for radio transients (Hyman et al. 2002, 2003).

GCRT J1745–3009 is a novel bursting radio source (Hyman et al. 2005), whose notable properties include “flares” approximately 1 Jy in magnitude lasting approximately 10 min. each and occurring at apparently regular 77 min. intervals. This object is located about  $1.25^\circ$  south of the Galactic center (GC, Figure 1) and was identified from 330 MHz (90 cm) observations with the Very Large Array (VLA) on 2002 September 30.

The source GCRT J1745–3009 is notable because it is one of a small number of *radio-*

*selected* transients. Moreover, with only a few exceptions (Melrose 2002) such as electron cyclotron masers from flare stars and the planets, plasma emission from solar radio flares, pulsar radio emission, and molecular-line masers, most radio transients are incoherent synchrotron emitters. For an incoherent synchrotron emitter, the energy density within the source is limited to an effective brightness temperature of roughly  $10^{12}$  K by the inverse Compton catastrophe (Readhead 1994). The properties of GCRT J1745–3009 suggest strongly that its brightness temperature exceeds  $10^{12}$  K by a large factor and that it is a member of a new class of coherent emitters.

The discovery observations of GCRT J1745–3009 were based on VLA 330 MHz observations at a single epoch, from which only a limited amount of information about the source could be gleaned. This paper reports on a second detection of GCRT J1745–3009, made with the Giant Metrewave Radio Telescope (GMRT) in 2003, as well as on a series of 330 MHz nondetections resulting from archival observations and our Galactic center radio transient monitoring program. The observations are summarized in §2 and the results in §3. We discuss briefly the environment of the source in §4, and we present our conclusions in §5.

## 2. Observations

Table 1 summarizes the 330 MHz observations with the two telescopes. Most observations consist of a few, long scans with occasional interruptions for phase calibration (see below). At a few epochs, however, the duration of the observations was not obtained in a single observation, but in multiple, short and widely spaced scans. About half of the observations had durations shorter than the 77 min. burst period observed in 2002. At both telescopes, both right- and left-circular polarization were recorded.

The flux density of GCRT J1745–3009, even at its peak, is far less than the total flux density contributed by other sources in the field of view. Thus, the source can be detected only in images. In turn, because of the relatively large fields of view and the number of sources within the field of view, the entire field of view must be imaged.

Production of the images was conducted in a consistent manner from epoch to epoch. Calibration of the flux density was by reference either to 3C 48 or 3C 286. Initial calibration of the visibility phases was obtained by observations of a nearby VLA or GMRT calibrator, typically J1714–252. At 330 MHz, radio frequency interference (RFI) can be a substantial problem, and, if not excised from the visibility data, it would limit the dynamic range of the final image. We examined the visibility data for RFI and excised it.

At 330 MHz, neither the VLA nor the GMRT can be assumed to be coplanar; in order

to image the entire field of view, we used a polyhedral imaging algorithm to compensate for the non-coplanarity of the arrays (Cornwell & Perley 1992). In order to approach thermal noise limits in the images, several iterations of imaging, deconvolution (CLEANing), and self-calibration were used. In order to search for bursts from GCRT J1745–3009, the CLEAN components of all other sources in the field were subtracted from the  $u$ - $v$  data, and the residual data were then imaged in 10 min. subsets. Noise levels of the 10 min. images range from approximately 10 mJy beam<sup>−1</sup> for the GMRT and 20 mJy beam<sup>−1</sup> for the most extended VLA configurations (A and B) to approximately 250 mJy beam<sup>−1</sup> for the more compact configurations (C and D), which have both a lower angular resolution and are more susceptible to RFI and sidelobe confusion. If a burst was detected, the residual data then were imaged with a higher time resolution (from 5 to 30 s) in order to search for structure within the burst.

All but four of the VLA observations listed in Table 1 are pointed in the direction of Sgr A\*, approximately 1.25° north of GCRT J1745–3009. (Coincidentally, the discovery observations were pointed nearly directly at the source.) The GMRT observations are pointed approximately 0.5° west. The primary beam attenuation of the VLA and the GMRT reduces the apparent flux density of the source by a factor of approximately 2 and 1.5, respectively. While significant, this level of primary beam attenuation would not be sufficient to prevent the recovery of the source, provided that the amplitude of the bursts is approximately 1 Jy. However, if the bursts have a range of amplitudes, significantly weaker bursts ( $\lesssim 150$  mJy) could have gone undetected in the vast majority of our observations.

### 3. Results

We detect GCRT J1745–3009 at two epochs, 2002 September 30–October 1 and 2003 September 28. The latter epoch is a new recovery of the source, while the former epoch is that of the discovery by Hyman et al. (2005). Figure 2 shows contour images before, during, and after the fourth burst detected on 2002 September 30. Figure 3 shows the light curves for the five 2002 September 30 bursts, with 30-s sampling, and the 2003 September 28 burst with 17-s sampling. Unfortunately, the recovery observation on 2003 September 28 consisted of approximately 10 min. scans spaced approximately an hour apart for several hours. Only a single burst, already in its decay phase, is detected at the beginning of a scan (2003 September 28 11:44:53, IAT). As shown in Figure 3, the shape of the decay profile for the 2003 September 28 burst is consistent with that seen for the 2002 September 30 bursts. Assuming that this burst is consistent in duration with those from 2002 September 30, the 2003 September 28 burst had a peak of approximately 0.5 Jy, compared to 1–1.5 Jy for those

on 2002 September 30. Clearly, a longer burst duration implies a higher peak flux density.

Figure 4 shows the fourth burst from 2002 September 30 with the full 5-s sampling. The steep decay of the bursts is depicted much more clearly with higher time resolution. We have fitted both the rising and decay portions of the bursts with an exponential function. None of the apparent structure in the light curves (Figure 3) is significant above the  $2\sigma$  level, and no significant structure is evident in the 5-s light curves that is not also present in the 30-s light curves.

The source is unresolved in both epochs. The angular resolution ( $20'' \times 10''$ ) and sensitivity ( $50 \text{ mJy beam}^{-1}$  for 17-s integrations) of the 2003 September 28 recovery observation is significantly improved over the 2002 September 30 discovery observation. Fitting a Gaussian to the source yields a position of (J2000) right ascension  $17^{\text{h}} 45^{\text{m}} 5^{\text{s}}.23 (\pm 0^{\text{s}}.38)$ , declination  $-30^{\circ} 09' 53'' (\pm 5'')$ , which is approximately a factor of two more accurate in each dimension than determined in the 2002 September 30 observation.

Observations at 330 MHz are affected strongly by ionospheric phase fluctuations. Their impact includes refractive position shifts. We used eight nearby small-diameter sources from the NRAO VLA Sky Survey (NVSS) (Condon et al. 1998) to register our images. The NVSS was conducted at 1400 MHz and has a substantially better astrometric accuracy of  $0''.5$  in both right ascension and declination for bright sources. We found an average ionospheric-induced refraction of  $0^{\text{s}}.23 \pm 0^{\text{s}}.24$  in right ascension and  $-4''.6 \pm 3''.4$  in declination. The source position and uncertainty cited above include a correction for this refraction.

No frequency dependence was detected in the 2002 September 30 bursts, and none is detected across the 60-channel, 15-MHz bandpass for the 2003 September 28 burst. A power-law fit across the 15-MHz bandpass of the 2003 September 28 observation yields a wavelength dependence of  $S \propto \lambda^{4 \pm 5}$ . No circular polarization is detected in the bursts with an upper limit of 15% obtained for both epochs. Linear polarization measurements are not available for either the discovery or recovery observations.

No emission is detected from GCRT J1745–3009 when imaging the 2003 September 28 observation at times when the burst is not occurring. We are able to improve the ( $5\sigma$ ) upper limit for 330 MHz interburst emission from 75 mJy, for the discovery observations, to 25 mJy, for the recovery observation. The upper limit on quiescent emission during periods of no burst activity is 15 mJy at 330 MHz (Hyman et al. 2005). Nondetections on 2005 March 25 at both 330 and 1400 MHz also yield an upper limit of 15 mJy at 330 MHz, but a significantly reduced upper limit of 0.4 mJy at 1400 MHz, as compared to a 35 mJy upper limit obtained from a 2003 January observation at that frequency. We have also learned that GCRT J1745–3009 has been observed in early and mid-2005 with the Westerbork Synthesis

Radio Telescope (WSRT) at both 330 and 1400 MHz. Upper limits on any emission are approximately a few milliJanskys (R. Braun 2005, private communication).

As Hyman et al. (2005) reported, during the discovery epoch (2002 September 30–October 1) the bursts from the source had an approximate 77 min. periodicity. As noted above, the recovery on 2003 September 28 occurs in the midst of a set of 10-min. scans, spread over several hours. Assuming that the source was emitting periodic bursts at this epoch, each of 10 min. duration, we have determined the periods at which bursts could occur while being consistent with the gaps and non-detections during the 2003 September 28 epoch. There are 212 min. between the detected burst and the end of the observation. Thus, we can place no constraints on periods longer than 212 min. For shorter periods, only the following ranges of periods are allowed: 36–37 min., 71–78 min., 107–112 min., 131–160 min., and 179–195 min. We estimate that the uncertainty in making these determinations is perhaps 1 min. and results from slightly varying noise levels within the scans and the assumption that the duration of the bursts remains fixed at 10 min. Thus, while consistent with the gaps and non-detections, the possible 36–37 min. periodicity is perhaps only marginally so. A 77 min. periodicity remains consistent with the 2003 September 28 observations.

We cannot use the interval between 2002 September 30 and 2003 September 28 to constrain the burst activity because the uncertainty on the 77 min. period determined from the 2002 September 30 observations is sufficiently large ( $\sim 15$  s) that we cannot connect the phase between the two observations. Indeed, the nearest observation to the 2002 September 30 observation precedes it by 70 days while the nearest to the 2003 September 28 observation, other than that on 2003 September 29, follows it by 16 days. The current uncertainty is large enough that a single burst could not be connected in phase over these intervals, even if the source had been detected. In addition, the sparse sampling of the observation made one day after the 2003 September 28 detection does not include any scan at multiples of 77 min. later, nor do the scans, when taken together with those on September 28, significantly alter the allowed ranges of other periods given above. Thus, we cannot use the nondetection on 2003 September 29 to place limits on the duration of the active period of the source.

The 2003 September 28 and 29 observations were part of a series of GMRT observations designed to survey the entire Galactic center region. These include a number of other pointings, not included in Table 1, that potentially could be used to detect GCRT J1745–3009, albeit with much larger primary beam attenuation. In particular, there are scans on Sgr A, some  $1.3^\circ$  away from both GCRT J1745–3009 and the recovery observation’s pointing center, that end approximately 10 min. before, 77 min. before, and 154 min. after the decay portion of the burst detected in the recovery observation. We estimated the amount of primary beam attenuation by measuring the peak flux density of *Sgr A* from the recovery observation of

GCRT J1745–3009. The primary beam attenuation is approximately a factor of 10. Thus, in the scans on Sgr A, if the transient were bursting at the level of about 1 Jy, it would appear as a 100 mJy source. Such a source would still be well above the noise level in the images for each scan, but GCRT J1745–3009 is not detected in any of them. Thus, the upper limit for the duration of the detected burst is approximately 13 min. and consistent with the 10 min. duration observed for the 2002 September 30 bursts. Furthermore, the 77 min. period and the range of other periods allowed by considering only the recovery observation scans (see above) are largely ruled out by nondetections in the Sgr A scans from 2003 September 28. Thus, this burst appears to be an isolated one, in contrast to the 2002 September 30 bursts.

Finally, we note that our northern GC-pointed GMRT scans, centered  $\sim 2^\circ.5$  to the north-east of GCRT J1745–3009 and the bright source, Sgr E 46 (see Figure 2), detect Sgr E 46, but at a very low level due to severe primary beam attenuation ( $\sim 200\times$ ). One of these northern pointings lasted from 11:36 to 11:44 on 2003 September 28, just before the burst’s decay phase was detected at 11:45 at the beginning of the southern pointing that followed. Since Sgr E 46 is located only  $0^\circ.1$  closer to the pointing center than GCRT J1745–3009, we have corrected the 5 min. noise level at the position of GCRT J1745–3009 by the  $\sim 200\times$  primary beam attenuation factor to crudely estimate the upper limit of the peak of the 2003 detected burst. An upper limit of  $\sim 5$  Jy is obtained, consistent with the 1.5 Jy peak values observed in the 2002 bursts. However, we consider this result and the evidence that the burst is an isolated one to be very tentative, since the location of GCRT J1745–3009 is very far out on the primary beam for these pointings, and since the beam shape could be asymmetric.

As an initial crude estimate for the duty cycle of the bursting behavior of GCRT J1745–3009, we compare the time during which the source is observed to be active to the total amount of observing time. The total observing time is almost exactly 70 hr. The 2002 September 30 bursts lasted for at least 6 hr; because only a single burst was detected on 2003 September 28, we assume that the source was active for 1 hr. Thus, the apparent duty cycle of GCRT J1745–3009 is approximately 10%.

Finally, we note that both the original discovery and the recovery observation occur in late September and are separated by  $\sim 1$  yr. However, given that the discovery and recovery observations occurred with different telescopes and that there was no detection in our 6-hr 1998 September 25 observation, we can identify no seasonal nor instrumental explanation that would indicate that the source is not a celestial object. By analogy with the model proposed by Turolla et al. (2005), it might be the case that the activity of GCRT J1745–3009 results from orbital motion with an approximate 1-yr period. However, any such model would also have to explain the non-detections in the 1998 September 25 and 26 epochs.

#### 4. Environment of GCRT J1745–3009

If GCRT J1745–3009 is located at the Galactic center, prevailing models explain it as a compact object, most likely a neutron star (e.g., Turolla et al. 2005). Motivated by a prediction in Turolla et al. (2005), we have examined images that contain the field around GCRT J1745–3009 in an effort to detect any faint nebulosity, such as might result from a supernova remnant. We have examined images at 330 MHz (LaRosa et al. 2000; Nord et al. 2004), 1400 MHz (Yusef-Zadeh et al. 2004), and  $2\ \mu\text{m}$  (2MASS); the number of images that we can search is small because the location of the source is outside of the field of view of many images of the Galactic center region.

As seen in Figure 1, GCRT J1745–3009 is located approximately  $10'$  from the center, and just outside, of the shell-type supernova remnant SNR G359.1–0.5 (Reich & Fürst 1984). At a distance of  $8D_8$  kpc, this angular distance corresponds to a transverse distance of approximately  $25D_8$  pc. The SNR itself is old, as evidenced by its size and the extent to which the shell appears “broken up.” Assuming that its age is  $10^5 T_5$  yr, if GCRT J1745–3009 and the SNR are related, then GCRT J1745–3009 would have to have a velocity of about  $225D_8/T_5$  km s $^{-1}$  to have reached its current location. This velocity is well within those observed for neutron stars detected as pulsars (Arzoumanian et al. 2002).

In general, there is no diffuse emission surrounding the location of GCRT J1745–3009. One possible exception is some faint emission from the shell of SNR G359.1–0.5, which lies about  $1'$  north of the position of the transient. While this close proximity could be indicative of a connection between the SNR and GCRT J1745–3009, there is otherwise no distortion in the shell of the SNR, akin to that seen for G5.4–1.2 and PSR B1757–24 (Frail & Kulkarni 1991), nor does GCRT J1745–3009 have a cometary appearance similar to a pulsar wind nebula (PWN) like the Mouse (Gaensler et al. 2004).

#### 5. Conclusions

We have summarized a series of Very Large Array and Giant Metrewave Radio Telescope observations of GCRT J1745–3009 (Table 1). We detect GCRT J1745–3009 at two epochs, 2002 September 30–October 1 and 2003 September 28. The latter epoch is a new recovery of the source, while the former epoch is that of the discovery by Hyman et al. (2005).

The two sets of detections of GCRT J1745–3009 are consistent with the source producing approximately 1 Jy bursts; we cannot exclude the possibility that the source produces significantly weaker bursts ( $\lesssim 150$  mJy) more frequently. Hyman et al. (2005) reported that the bursts appear to have a  $77.1 \pm 0.3$  min. periodicity; we have provided tentative evidence

indicating that the 2003 September 28 burst is an isolated one. Given the epochs of observations, we estimate crudely that the source is active for approximately 7 hr, and the apparent duty cycle of its activity is roughly 10%.

We have examined the field around GCRT J1745–3009 at radio and infrared wavelengths. We find possible nebulosity at 1.4 GHz in the shell of SNR G359.1–0.5 near the location of the source, but otherwise no connection between the SNR and the transient. The velocity required for GCRT J1745–3009 to have originated at the center of SNR G359.1–0.5 and reached its current transverse separation is only roughly  $225 \text{ km s}^{-1}$ . While well within the range of velocities observed for various neutron stars, there is also no compelling reason to think that GCRT J1745–3009 and the SNR are related.

Additional observations are required to determine more about the nature of GCRT J1745–3009. As well as additional searches such as those that we report here, infrared observations to search for a counterpart, a periodicity search for weaker pulsed emission, and X-ray observations to search for quiescent X-ray emission would all be useful.

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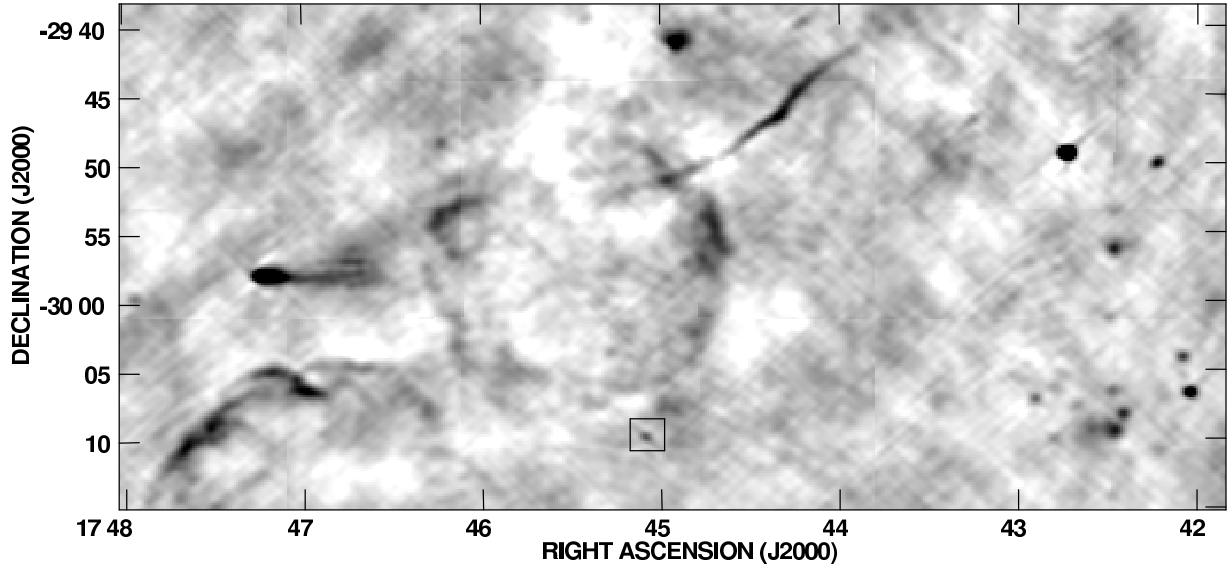


Fig. 1.— Image of the Galactic center field at 330 MHz from the discovery observations on 2002 September 30 (Hyman et al. 2005). The transient source GCRT J1745–3009 is indicated by the small box below the approximately 20′ diameter shell of SNR 359.1–00.5. The resolution and sensitivity of the image are  $48'' \times 39''$  and  $15 \text{ mJy beam}^{-1}$ , respectively. GCRT J1745–3009 appears as a 100 mJy source here since it is averaged over five, short ( $\sim 10 \text{ min.}$ ), roughly 1 Jy bursts out of a total of a 6-hr observation. Other sources in the field of view include the sources to the west which are part of Sgr E, the Snake is the linear feature to the north, and the Mouse is northeast of GCRT J1745–3009.

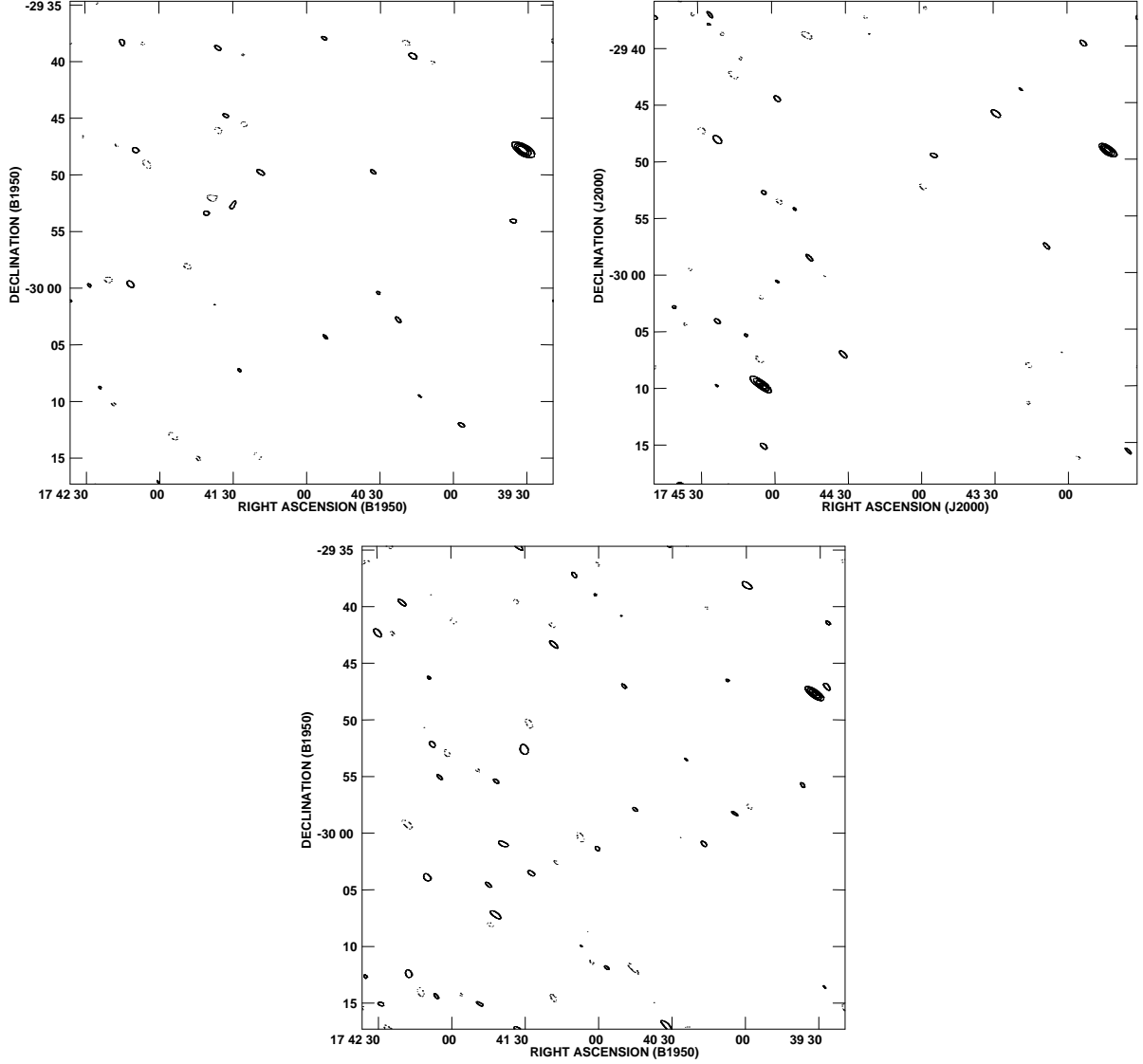


Fig. 2.— A 330 MHz VLA image of the field surrounding GCRT J1745–3009 and the source Sgr E 46 (at upper right in each image) made in 5-min. intervals just before (top left), during (top right), and just after (bottom) the fourth burst detected in 2002 September 30. The fourth burst is shown because sampling of it is complete. Most of the bursts detected in this epoch were sampled only partially due to (unfortunately-timed) interruptions for phase calibration. The transient is located at the bottom left in the center image. The contour levels are  $-0.4, 0.4, 0.7, 1.0$ , and  $1.3 \text{ Jy beam}^{-1}$ .

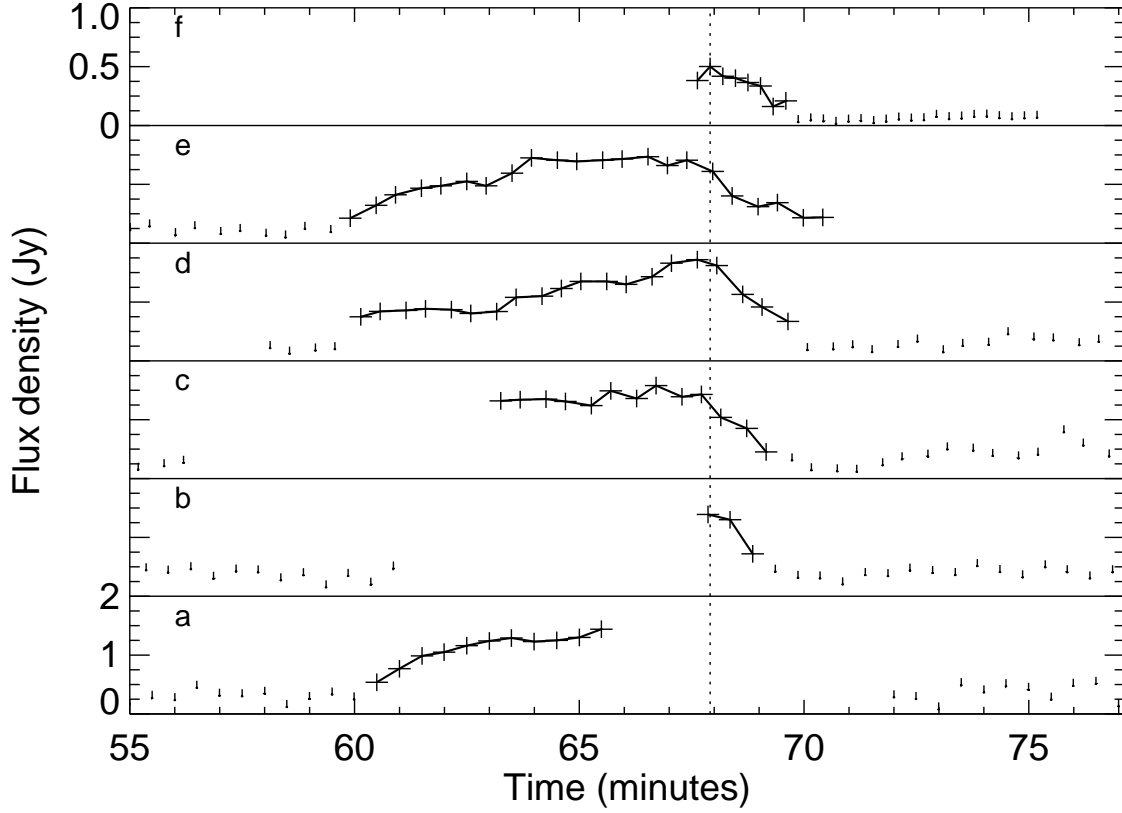


Fig. 3.— The light curves of GCRT J1745–3009. The top panel shows the single detected burst from 2003 September 28 with 17-s sampling; the remaining panels show the bursts from 2002 September 30 with 30-s sampling (Hyman et al. 2005), arranged with the fifth burst shown in the second panel to the first burst in the bottom panel. For the 2002 September 30 bursts, the light curve has been folded at the apparent 77.1 min. periodicity. For the 2003 September 28 burst, the light curve has been aligned in time to be consistent with the decay portions of the 2002 bursts. In many cases, because the existence of GCRT J1745–3009 was not known at the time of the observation, the full burst is not captured because the observations were interrupted for calibration observations. The 2003 September 28 observations consisted of one 7 min. scan per hour for several hours. The arrows represent  $3\sigma$  upper limits for nondetections.

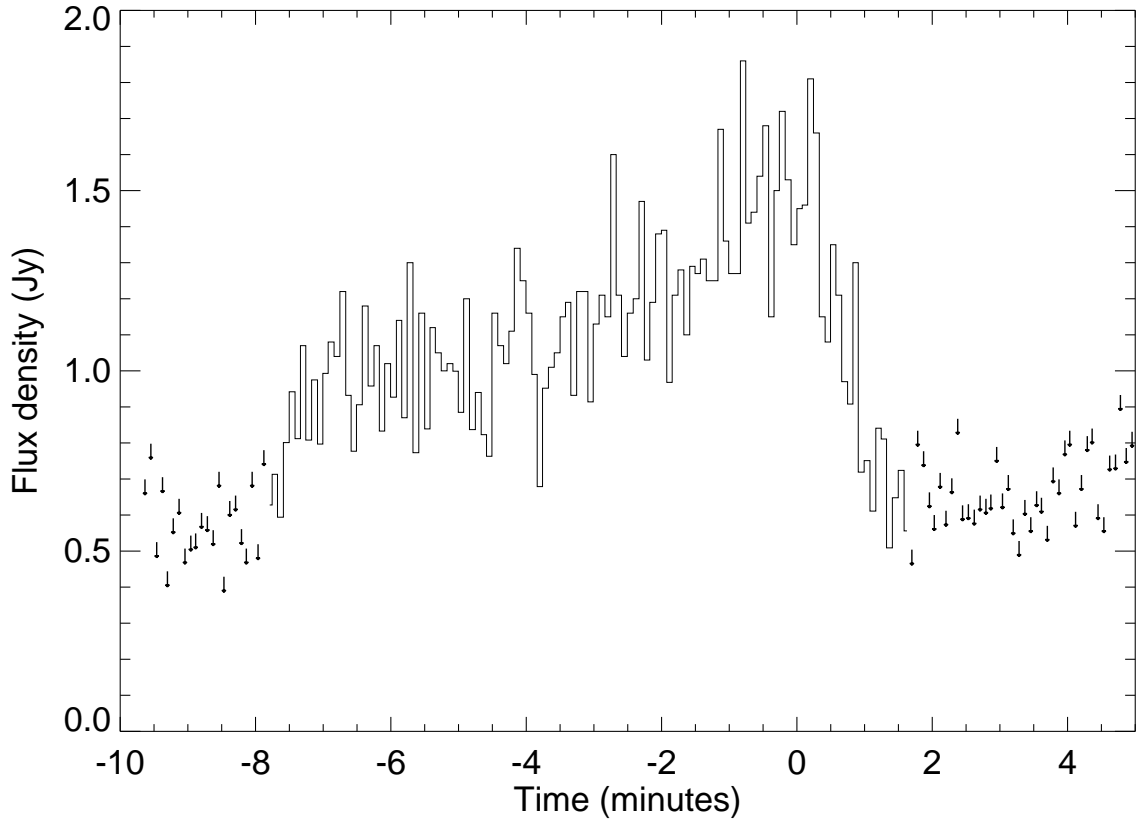


Fig. 4.— The fourth burst detected in the 2002 September 30 observations shown with the full 5-s sampling. The arrows represent  $3\sigma$  upper limits for nondetections.

Table 1. 330 MHz Observational Log

Epoch <sup>a</sup>		Telescope <sup>b</sup>	Bandwidth (MHz)	Duration (min.)
1989 March 18	09:49:40	VLA:B	12.5	331.8
1995 October 14	22:49:40	VLA:B	1.6	30.7
1996 October 19	23:03:30	VLA:A	6.2	173.5
1996 October 19	19:48:50	VLA:A	6.2	176.0
1997 February 06	13:57:10	VLA:BnA	6.2	76.7
1998 November 29	16:52:20	VLA:C	3.1	380.7
1998 September 26	02:24:30	VLA:B	3.1	124.0
1998 September 25	21:08:00	VLA:B	3.1	277.5
1998 March 14	14:40:50	VLA:A	3.1	98.8
1998 March 14	10:06:10	VLA:A	3.1	231.8
1999 May 31	04:53:00	VLA:D	3.1	376.7
2001 September 05	00:40:60	VLA:C	3.1	181.3
2002 March 26	10:46:30	VLA:A	6.2	29.7
2002 March 26	11:18:50	VLA:A	6.2	34.7
2002 April 27	09:10:40	VLA:A	6.2	83.8
2002 May 17	08:51:50	VLA:AB	6.2	83.8
2002 June 24	09:22:00	VLA:B	6.2	34.5
2002 July 21	06:05:60	VLA:B	6.2	59.2
2002 September 30 <sup>c</sup>	20:48:30	VLA:BC	6.2	289.7
2002 October 01 <sup>c</sup>	02:34:45	VLA:BC	6.2	53.8
2003 January 20	15:27:40	VLA:CD	6.2	187.8
2003 July 05	08:09:50	VLA:A	6.2	34.5
2003 July 08	06:28:10	VLA:A	6.2	59.2
2003 July 12	04:12:50	VLA:A	6.2	34.7

Table 1—Continued

Epoch <sup>a</sup>		Telescope <sup>b</sup>	Bandwidth (MHz)	Duration (min.)
2003 July 14	04:04:60	VLA:A	6.2	34.5
2003 July 28	07:09:20	VLA:A	6.2	34.5
2003 August 09	01:52:50	VLA:A	6.2	59.2
2003 August 18	23:43:40	VLA:A	6.2	59.2
2003 September 28 <sup>c,d</sup>	10:06:26	GMRT	15	63
2003 September 29 <sup>d</sup>	11:51:10	GMRT	15	45
2003 October 14	00:32:50	VLA:AB	6.2	59.2
2003 October 21 <sup>d</sup>	07:27:09	GMRT	15	45
2003 October 24	00:23:30	VLA:B	6.2	59.0
2003 November 23	21:16:40	VLA:B	6.2	39.7
2003 December 29	18:55:10	VLA:B	6.2	64.0
2005 March 25	13:13:30	VLA:B	5.0	72.0

<sup>a</sup>We provide the IAT start time of the observation for use in a later analysis. However, depending upon the observing program, the duration of the observation may not have been obtained in a single observation, but in multiple shorter ones at the epoch.

<sup>b</sup>The notation “VLA:A” refers to the A configuration of the VLA.

<sup>c</sup>Source detected at this epoch.

<sup>d</sup>This epoch consists of multiple, short scans taken over several hours.